

Evolving Stellar Background Radiation and Gamma-Ray Optical Depth

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Abstract. We present a semi-empirical model for the evolving far-infrared to ultraviolet diffuse background produced by stars in galaxies. The model is designed to reproduce the results of deep galaxy surveys, and therefore may be considered as a cosmology-independent lower limit to the extragalactic background light. Using this model and recent HEGRA data, we infer the intrinsic spectrum at multi-TeV gamma-ray energies for Mkn 501 and find that it is consistent with a power law of spectral index 2.49 ± 0.04 . In turn, this finding renders it rather unlikely that the present-day infrared background has an intensity as high as claimed by Finkbeiner et al. [1]. Future 10 GeV to TeV observations could be used to either constrain the ultraviolet-to-infrared background model at high redshifts or cosmological parameters.

INTRODUCTION

High-energy gamma-rays originating from sources at cosmological distances can be absorbed by pair production in collisions with low-energy photons. Most of the low-energy photons are produced by stars in ordinary galaxies and contribute to the extragalactic background light (EBL). The role of other contributors, such as Active Galactic Nuclei, is under dispute, and can safely be assumed to be unimportant in terms of the global energy budget. To model the stellar component of the EBL, we use an approach similar to that used in Refs. [2–4], however with the star formation rate (SFR) inferred from deep multi-color galaxy surveys. Other approaches aim at finding an *ab initio* description of the SFR from the theory of structure formation [5]. Knowing the EBL as a function of redshift, one can calculate the optical depth with respect to pair creation and determine the propagation length of gamma-rays from cosmologically distributed sources such as Blazars or Gamma Ray Bursts [2,5].

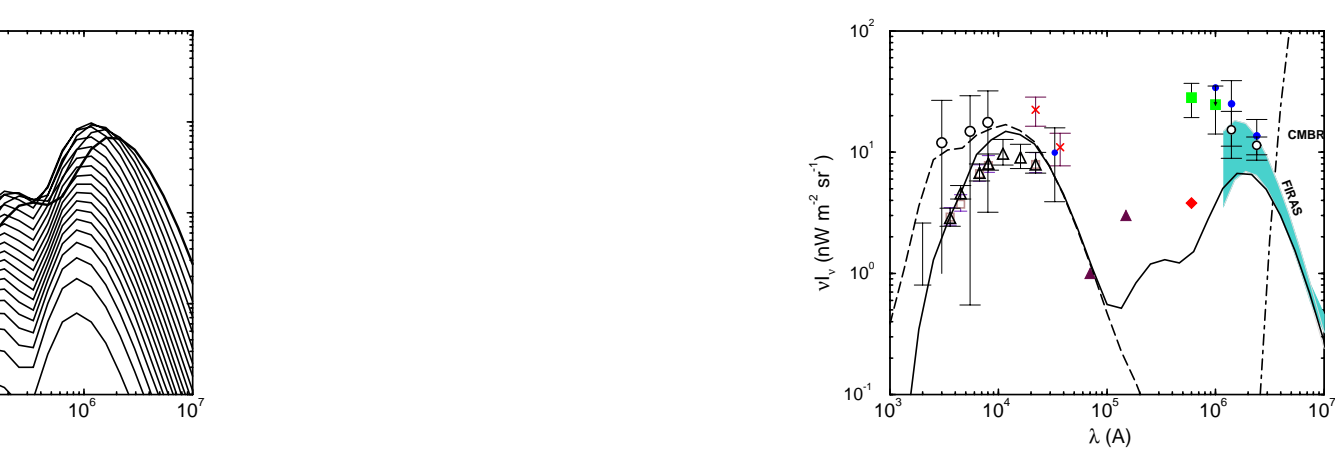


FIGURE 1. *Left panel:* Evolution of EBL from $0 < z < 5$ ($\Delta z = 0.2$). ($E_{B-V}=0.14$, $T_1=150$ K, $T_2=35$ K, $\alpha=3.5$, $\beta=-1$, $z_p=1.3$, $\dot{\rho}_*(z_p)=0.15$). *Right panel:* Present-day EBL with (solid line) and without (long dashed line) absorption. Data are Refs. from [10](open triangles and squares/HST), [11](circles), [12](filled circle at $3.5 \cdot 10^4 \text{Å}$ /DIRBE), [13]("x"), [14](triangles), [1](squares), [15](diamond/IRAS, filled circles/DIRBE), [16](open circles), [17](shaded band, FIRAS detection $1.25 \cdot 10^4 \text{Å}$ - $50 \cdot 10^4 \text{Å}$).

EBL-MODEL

We start with the spectrum of an evolving simple stellar population (SSP) [6] (solar metallicity, Salpeter IMF $0.1\text{-}100 M_\odot$). Next, we include absorption and re-emission effects (dust and gas of ISM) using a SMC-like extinction law (E_{B-V}) and two modified blackbody spectra for the re-emission from dust ($T_1 > T_2$). The Star Formation Rate (SFR) is $\dot{\rho}_*(z) \propto (1+z)^{\alpha,\beta}$ with slopes α for $z \leq z_p$ and β for $z > z_p$, and a peak value $\dot{\rho}_*(z_p)$. By choosing proper parameters, the emissivities $\epsilon_\nu(z)$ obtained from integrating the SFR-weighted SSPs are brought to agreement with the data. A second integration from z to z_{max} yields the EBL comoving power spectrum (Fig. 1) which is independent of cosmology due to a cancellation of the cosmology-dependent terms. The EBL increases from high redshifts towards the present, but saturates at a roughly constant level beyond the peak in the SFR. The EBL spectrum at high z is dominated by young, UV-emitting massive stars. 70% of the energy released by stars is re-emitted by dust in the infrared and far-infrared bands. The spectrum changes towards its present shape as a result of a growing admixture of aged stars. About 40% of the integrated present-day EBL is contained in the IR (between 10^5Å and 10^7Å)(see Fig.1 and for details Ref. [7]).

GAMMA-RAY ATTENUATION

The pair creation optical depth $\tau_{\gamma\gamma}(E, z)$ for gamma-rays at cosmological redshift z and observed energy E is defined as the ratio of coordinate distance and mean



FIGURE 2. *left panel:* Pair-creation optical depth for gamma-rays for a range of redshifts ($0.03 < z < 5$). *right panel:* Gamma ray horizon defined by $\tau(z, E) = 1$ for various models.

free path [2]. The optical depth evaluated for our EBL and a range of redshifts ($0.03 < z < 4$) is shown in Fig.2 ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega = 1$, and $\Omega_\Lambda = 0$).

We can use the optical depth of gamma-rays to infer the intrinsic spectrum of Mkn501 from recent data. This is achieved by simply multiplying the data with the factor $\exp[\tau_{\gamma\gamma}(0.034, E)]$, and the result is shown in Fig.3.

The gamma-ray horizon $\tau_{\gamma\gamma}(z, E) = 1$ defines an interesting relation between distance and cut-off energy. In contrast to the EBL, the gamma-ray horizon depends on cosmology through the integration over a cosmic line element dl/dz . If we switch from a standard Cold Dark Matter model (Fig.2, *right panel*, solid line) to one with a lower matter density (dashed line, $\Omega_\Lambda = 0.7$), the horizon moves closer and the number of sources which can be detected above a given gamma-ray threshold energy decreases. The effect could also be mimicked by a flatter SFR [8].

CONCLUSIONS

We have developed a simple model for the evolution of the extragalactic background radiation field using a minimum number of parameters by fitting the emissivity predicted by the model to recent results of high-redshift galaxy surveys. Future improvements will include metallicity effects and a PAH feature around $10\mu\text{m}$. The intrinsic spectrum of Mkn501 inferred from our model is in good agreement with theoretical predictions (see Ref. [9] for a discussion) rendering claims for an extremely high level of the infrared background light intensity implausible. The EBL model is a powerful tool to analyze gamma-ray spectra from high-redshift sources in the 10 GeV to TeV regime for which the pair attenuation occurs in interactions with ultraviolet-to-infrared photons allowing to probe the era of maximum star formation or cosmology.

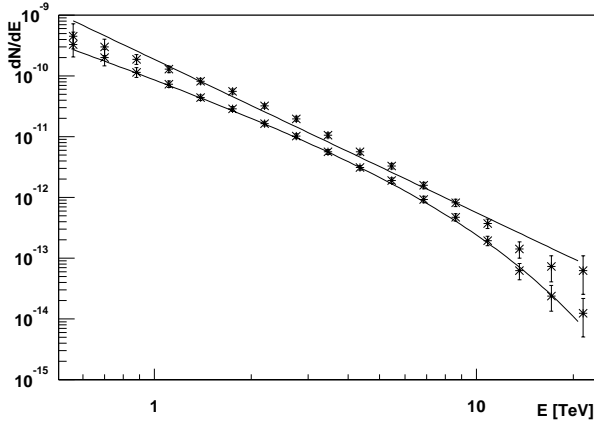


FIGURE 3. Intrinsic spectrum of Mkn501 inferred from our EBL model (*upper stars*) and fitted by a power law with index 2.49 ± 0.04 (*upper line*). HEGRA original data from Ref. [18] (*lower stars*) and power law times exponential fit (*lower line*) from Ref. [19] are shown for comparison.

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